DEVELOPMENT OF A WIRELINE CPT SYSTEM FOR MULTIPLE TOOL USAGE

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INTRODUCTION

Cone penetrometer technology (CPT) has received widespread interest and is becoming more commonplace for environmental site characterization activities at most DoE facilities. The primary reason for CPT's widespread usage is the significant advantages offered by CPT techniques. For example, CPT is typically faster and less expensive than drilling techniques (Booth, et al. 1993). In addition, CPT provides higher quantity data with significantly more detail in defining subsurface conditions. CPT generates very little drilling waste, offering significant cost savings for operations in contaminated soils (Schroeder, et al. 1991). Although CPT already offers many benefits, the technology can be improved to offer increased utility and cost savings with the development of an innovative wireline CPT system.

The proposed wireline CPT system consists of an assortment of tools that can be pushed using standard CPT rigs and equipment. The novel aspect of this approach is that various tools can be placed at the tip of the rod string depending on the type of information or sample matrix desired. Tools can be swapped at any depth and different tools can be used to allow nearly all work to be accomplished in a single penetration, as opposed to the multiple penetrations currently conducted if more than CPT data is required.

The development of a wireline system for use with CPT equipment will result in a major reduction in both the time required to accomplish various tasks and in the cost of performing the work. The wireline concept will also allow development of new methods for installing monitoring points and sensors as well as for installing various pressure-injected barriers. Specific applications of the wireline technology includes:

- the use of the sonic approach with CPT sensors at SRS for very deep penetrations,
- installation of vadose monitoring points around the Hanford tanks for leak detection purposes, and
- eventual deployment into the tank waste materials using the Hanford tank farm CPT unit to obtain both in situ waste information and confirmation samples in a single riser deployment without disturbing the materials under two risers.

OBJECTIVES AND APPROACH

CPT has been effective at increasing the speed and reducing the cost of site characterization, but there is room for further improvement. Specifically, reducing the number of penetrations per test location while increasing the ability to collect a greater variety and quantity of data during a single penetration would greatly enhance the utility and cost effectivness. Towards this objective, our approach was to develop a unique wireline tool system for CPT that allows multiple CPT tools to be interchanged during a single penetration, without withdrawing the CPT rod string from the ground. Included in this set of tools are:

- A small diameter (1.125-inch) piezocone,
- Grout module,
- Tool locking and retrieval mechanism, and
- Soil sampler.

PROJECT DESCRIPTION

The project is divided into a base contract and two options. Under the base contract, the wireline rod string, tool locking mechanism, and two interchangeable tools -- a piezocone module and a grouting module -- were developed and evaluated.

During Option 1 of the contract, a wireline soil-sampler will be developed to allow the collection of soil samples from multiple depths during a single penetration. The wireline soil sampler will also facilitate cutting through and removing hard-to-penetrate materials, such as dense cemented soils, without withdrawing the rod string to change tips and remove samples.

Option 2 of the contract will consist of a 12-day evaluation at DoE's Hanford, Washington site. The objective of this demonstration will be to utilize the wireline CPT tools to perform baseline probing and monitoring point installations for the detection of radiation leaks around a high-level waste tank. Radiation leakage from the tanks will be evaluated and compared using both electrical resistance tomography (ERT) and hydrogen gas concentration monitoring *in situ*.

RESULTS

Wireline System Description

The wireline CPT system to date consists of five major components:

- 2-inch diameter flush threaded rod string,
- tool and lock housing (including cutting mouth),
- tool locking and retrieval mechanism,
- piezocone module, and
- grout module.

A photograph of a portion of the prototype system is presented in Figure 1. Depicted are the rod string and cutting mouth with piezocone tool installed.

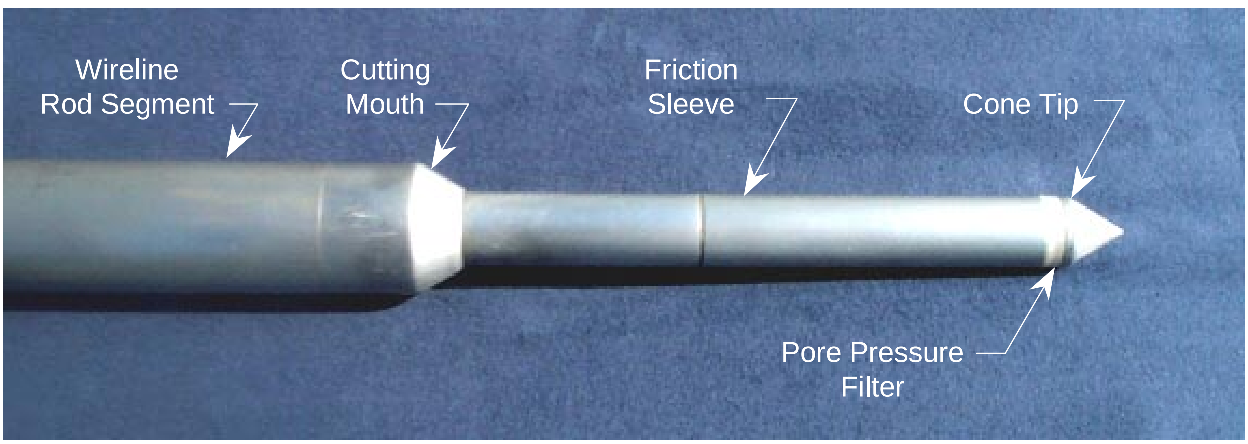

Figure 1. Photograph of Prototype Wireline CPT System with Piezocone Tool Installed.

Field Evaluation

The prototype wireline designs were demonstrated and evaluated during a one-week testing period conducted from 10 to 14 May, 1999 at the DOE's Savannah River Site (SRS). Cost estimates, penetration depths, and geotechnical characterization data were gathered for comparison to conventional techniques.

Site Description

The field evaluation was conducted at the M-basin of DOE's Savannah River Site (SRS), located in the northwest corner of the site, just south of the SRS administrative area. The M-basin was selected as the field evaluation location due to the diversity of geologic strata available at M-basin's Integrated Demonstration Area, the extensive history of prior site use for CPT evaluations, and the experience and familiarity of the on-site personnel with CPT operations and concepts. The prior experience of the site itself provides a plethora of data on soil conditions and the effectiveness of diverse types of CPT operations and innovations previously tested. Previous studies of the site have identified four clay layers and other significant stratigraphic variability in the upper reaches of the formation at the M-basin.

Test Procedures

Testing operations adhered to generally accepted principles of standard CPT operation and to the provisions of the applicable health and safety plans. For comparison to conventional CPT, the test matrix included a pair of conventional CPT soundings using an ASTM standard 1.75-inch piezocone (ASTM D6067-96). These soundings were conducted in close proximity to, and interspersed with, the wireline piezocone soundings. The time required to conduct a complete wireline piezocone sounding including pressure grouting upon rod retraction was recorded, as well as the time to complete a standard 1.75-piezocone sounding and grouting by re-penetration for comparison.

Retrieval and Re-deployment Reliability

The purpose of the first field testing task was to evaluate the reliability of the locking and release mechanism at multiple depths and in multiple geologies, and to determine the depth of refusal without using rod expanders, for comparison to conventional 1.75-inch diameter CPT rods under identical conditions. Additionally, the potential for binding of the individual wireline tools within the embedded rod string due to deflection was evaluated. These tests were accomplished by advancing a dummy (uninstrumented) cone tip to refusal using the wireline system, while repeatedly pausing (approximately every 2-meters) to release the locking mechanism, retrieve the dummy tool for inspection, and re-deploy it before continuing with the penetration. The removable tool was successfully retrieved and re-deployed with little or no difficulty at eleven depth intervals between 2.1 m (7.1 ft) and 16.2 m (53.1 ft) at location WL-2. Refusal was encountered at a depth of 16.2 m (53.1 ft).

Piezocone Validation and Refusal Depth

This test series allowed direct comparison, in nearly identical geologic conditions, of data obtained using the wireline piezocone with data obtained using an ASTM standard 4.4-cm (1.75-in) diameter cone. The calibrated 2.9-cm (1.125-in) diameter wireline piezocone was advanced to refusal without rod expanders twice, at locations WL-2A and WL-2B. Refusal was encountered at depths of 15.8 m (51.8 ft) and 15.7 m (51.6 ft) below ground surface (bgs), respectively, at these locations. The locations were horizontally separated by two meters. During each penetration, a hard layer was encountered at an approximate depth of 6.1 m (20 feet), which required liberal cycling to penetrate. Cycling is a common operational technique involving repeated retraction and re-advancement of the CPT rod string over a short depth interval (2 to 5 cm). This action results in cyclic unloading and loading of the force on the rods and underlying soil and allows for penetration to greater depth. The ability to cycle the wireline tool is an advantage over the use of a grout-through 4.4-cm (1.75-in) diameter piezocone, whose design does not support cycling.

Upon retrieval of the piezocone tool at both locations, slight binding of the tool within the rod string was observed at the 6.1-m (20-ft) depth, where a rod deflection due to the hard layer was apparent. At location WL-2A this deflection prevented re-deployment of the grout module within the rod string until the rod string was withdrawn to a depth of 6.7 m (22 ft) bgs. Pressure grouting was, however, successfully completed through the wireline grout tool at both of these locations. Production time data from the wireline piezocone penetration and subsequent pressure grouting at WL-2B were obtained for later comparison to the use of conventional CPT at an adjacent location.

To obtain both production time data and ASTM standard piezocone characterization data for comparison to the 2.9-cm (1.125-in) diameter wireline piezocone system, a conventional 4.4-cm (1.75-in) diameter piezocone penetration was completed at location WL-2C. WL-2C was located halfway between the two wireline piezocone penetrations (WL-2A and WL-2B). The sounding was completed uneventfully, without cycling, and provided the data necessary for the evaluation. The time and cost savings afforded by the wireline system are discussed in section 6.5 below. Results of validation of the wireline piezocone data are discussed in section 6.4.

At location WL-2D, another 4.4-cm (1.75-in) piezocone penetration was conducted, to provide confirmation of the previous conventional piezocone sounding and to determine refusal depth of a 4.4-cm (1.75-in) diameter rod string. WL-2D was located approximately one meter from WL-2B, and in line with WL-2A, WL-2B, and WL-2C. Refusal of this penetration was encountered at a depth of 44.5 m (146 ft) below ground surface (bgs).

Refusal Depth with Expanders

The final penetration was conducted at location 2E, using the wireline CPT system with rod expanders. Expanders are usually employed with CPT to decrease the friction along the side of the embedded rod by widening the hole, thereby improving the maximum depth of penetration. An expander is fabricated by welding a section of steel pipe to the outside of a rod segment. An expander is shown in Figure 2. A total of six one-meter, 2-in rods with 2.25-in diameter expanders were interspersed among the 35 one-meter rods in the wireline system rod string. Beginning directly behind the wireline lock housing, the rods with expanders were staggered so that the expanders were located in the 1st, 3rd, 5th, 7th, 11th, and 15th positions. Using this configuration, all available rod segments were used without encountering refusal. Total penetration depth was 33.2 m (109 ft) bgs. The locking mechanism released on the first tug and the piezocone was retrieved.

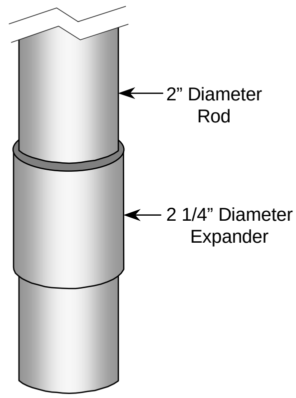

Figure 2. Depiction of a CPT Rod Expander.

Subsequently, the grout module was lowered down the embedded rod string. However, at a depth of approximately 16.2 m (20 ft), it would not pass a bend in the rod string. The difficulty was circumvented by unthreading the grout head from the locking mechanism, resulting in a shorter tool which easily passed the bend. With the high-pressure grout tube still attached, the locking mechanism was lowered to the bottom, where it engaged, and the hole was successfully pressure grouted to the surface using a total of 95 liters (25 gal) of grout. No problems were observed in grouting without the grouting head. The locking mechanism with the attached grout hose was found to perform sufficiently for grouting operations.

Reliability and Survivability

The individual wireline tools and locking mechanism are designed to withstand free-fall deployment (i.e., letting the tool fall freely through the rodstring engaging automatically once it reaches the lock housing). While initial bench testing of the wireline system components raised concerns regarding their ability to withstand repeated free-fall deployment, design changes were promptly implemented to harden shock-bearing elements of the tool locking mechanism. Subsequent bench and field testing resulted in no discernable damage, even with multiple free-falls to depths exceeding 16 meters (53 feet). Since the wireline rod string is more robust than that of conventional CPT equipment, its survivability as a component was not of concern.

The wireline piezocone tool, whose diameter is smaller than that of conventional cones, withstood repeated deployments through an extremely difficult-to-penetrate layer at the SRS M-Basin field testing site. In fact, the survival and continued performance of this component in an environment which required extensive cycling to penetrate and caused profound deflection of the robust 2-inch diameter wireline rod string, allays any concern regarding it's survivability.

Rod Deflection Interference

Conditions encountered in each penetration during the field evaluation were not likely to induce the most extreme deflection of the rod string that may ultimately be encountered in practice. However, four such penetrations were performed successively in an extremely difficult geology with only one notable interference to passage of the wireline tools. Thus confidence in the system's ability to perform successfully in practice is high. Additionally, consultation with site characterization authorities within DoE has indicated that 12 inches of core material for a wireline soil sampler would be sufficient for most needs. Thus we plan to shorten the length of each tool, originally designed to be compatible with a planned 18-inch core barrel, by six inches. This will likely eliminate the potential for binding during all conceivable operations.

Piezocone validation

Data obtained from the field evaluation at SRS were used to validate the wireline piezocone against the ASTM standard 1.75-in diameter cone. The data collected at the SRS site using the wireline, 1.125-in cone and the 1.75-in cone were statistically analyzed using the "Student *t*-test" statistical method.

The paired Student *t*-test computes the differences of paired data sets, to test the null hypothesis that the expected value (mean) of the differences is zero (Wonnacott and Wonnacott, 1985). The '*t*' test statistic is then used to estimate a probability for rejecting this hypothesis. In this case, the *t*-statistic as calculated for all paired combinations of the wireline 1.125-in cone and the ASTM 1.75-in cone. The data sets were truncated at a depth of 15.8 meters (51.7 feet), the depth of the shallowest penetration. Then, the tip stress, sleeve stress and pore pressure were transformed into $\log_{10}$, and data pairs were matched by depth. Then the mean and standard deviation of each population of differences could be determined to calculate the *t*-test statistic. The paired data sets included two 1.75-in cones, two 1.125-in cones and a 1.125-in cone with a 1.75-in cone. Figure 3 presents the tip, sleeve, and pore pressure data obtained from four adjacent penetrations conducted at SRS M-basin during the field evaluation.

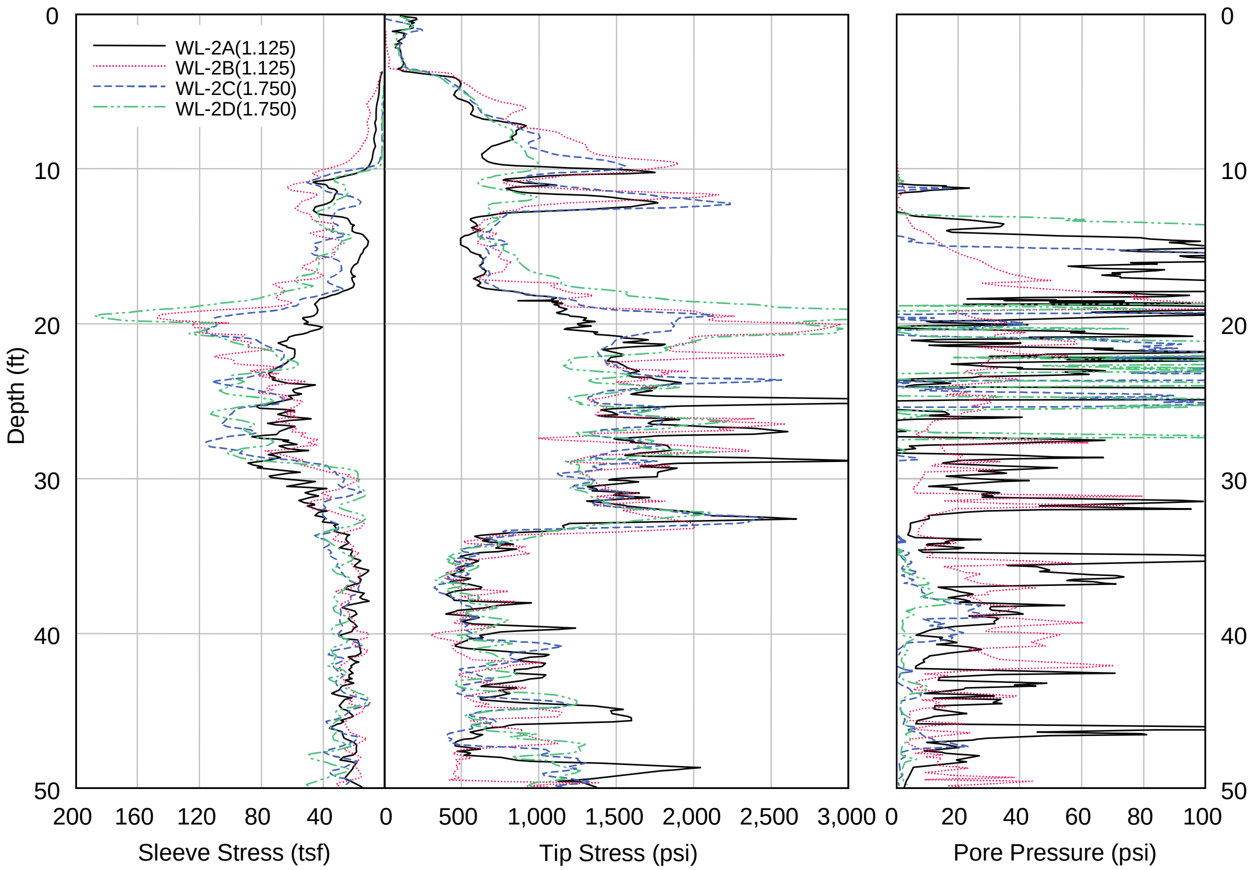

Figure 3. Tip stress, sleeve stress, and pore pressure data from a set of adjacent penetrations at SRS using two different piezocone geometries

Table 1, Table 2, and Table 3 list the statistical parameters calculated from the differences between the logs of tip stress, sleeve stress and pore pressure for adjacent pushes. Since the *t*- test assumes the data set follows a Gaussian distribution, the log of these parameters were used to transform the data closer to a normal distribution. The mean of the differences, the standard deviation and the number of measurements were used to calculate the *t*-test statistic. Each push consisted of approximately 400 to 500 points. The *t*-statistic tests the hypothesis that the expected value of the differences is zero and reveals information about the central tendency of the two data sets, but not about the variation, or distribution of the data. Since an inference on the variance of the differences in the data set is just as important as an inference on the mean, we will examine the variances both in independent pushes and the variance in the differences between paired data sets for the final report.

Table 1. Statistics of paired Tip Stress data from adjacent penetrations at SRS using Wireline Piezocone (WL-2A and WL-2B) and ASTM standard 1.75-in cone (WL-2C and WL-2D).

Pair	Note	Distance (m)	n	Mean $\square_d$	Standard Deviation S_d	*t*-Statistic 95% Confidence Interval ($t_{.025} = \pm 1.96$)	Result
WL-2A,WL-2C	WL & ASTM	0.9	550	-0.00916	0.13800	-1.55645	
WL-2A,WL-2D	WL & ASTM	3.5	550	-0.02214	0.17901	-2.90094	Reject
WL-2B,WL-2C	WL & ASTM	1.4	419	0.00680	0.16466	0.84563	
WL-2B,WL-2D	WL & ASTM	1.2	420	0.00461	0.17469	0.54090	
WL-2C,WL-2D	ASTM & ASTM	2.5	599	-0.01257	0.13931	-2.20780	Reject
WL-2A,WL-2B	WL & WL	2.4	550	-0.02638	0.18397	-3.36234	Reject

Note: WL = Wireline 1.125" Cone

The *t*-test statistic would indicate that at the 95% confidence interval there is a statistically discernable mean difference between the paired observations. In the comparisons of tip stress, this null hypothesis was rejected for three of the six paired distributions at the 95% confidence interval These three pairing represent combinations of both the same and different types of cones (ASTM 1.75-in and Wireline 1.125-in). The results indicate that, more often than not, the differences between two penetrations with different sized cones were less than the differences between two penetrations with identical cones. The t statistic for two pushes using the same cone (i.e. ASTM 1.75-in listed in Table 1, WL-2C, WL-2D, as –2.2078) is rejected at the 95% confidence interval. Looking at the distance between the pushes reveals that the paired data sets rejected at the 95% confidence interval were those for which the penetrations were separated by the greatest distance. This analysis shows that variations due to site heterogeneity are greater than any variation attributable to differences in cone geometry.

Table 2. Statistics of paired Sleeve Stress data from adjacent penetrations at SRS using Wireline Piezocone (WL-2A and WL-2B) and ASTM standard 1.75-in cone (WL-2C and WL-2D).

Pair	Note	Distance (m)	n	Mean $\square_d$	Standard Deviation S_d	*t*-Statistic 95% Confidence Interval ($t_{.025} = \pm 1.96$)	Result
WL-2A, WL-2C	WL & ASTM	0.9	561	0.026	0.350	1.776	
WL-2A, WL-2D	WL & ASTM	3.5	550	-0.005	0.331	-0.325	
WL-2B, WL-2C	WL & ASTM	1.4	417	0.173	0.396	8.943	Reject
WL-2B, WL-2D	WL & ASTM	1.2	420	0.130	0.370	7.187	Reject
WL-2C, WL-2D	ASTM & ASTM	2.5	595	-0.022	0.171	-3.094	Reject
WL-2A, WL-2B	WL & WL	2.4	550	-0.101	0.221	-10.766	Reject

Note: WL = Wireline 1.125" Cone

Table 3. Statistics of paired Pore Pressure data from adjacent penetrations at SRS using Wireline Piezocone (WL-2A and WL-2B) and ASTM standard 1.75-in cone (WL-2C and WL-2D).

Pair	Note	Distance (m)	n	Mean $\bar{x}_d$	Standard Deviation S_d	*t*-Statistic 95% Confidence Interval ($t_{.025} = \pm 1.96$)	Result
WL-2A, WL-2C	WL & ASTM	0.9	454	0.645	1.072	12.827	Reject
WL-2A, WL-2D	WL & ASTM	3.5	454	0.544	0.975	11.883	Reject
WL-2B, WL-2C	WL & ASTM	1.4	336	0.475	0.923	9.436	Reject
WL-2B, WL-2D	WL & ASTM	1.2	337	0.327	0.990	6.069	Reject
WL-2C, WL-2D	ASTM & ASTM	2.5	515	-0.074	0.771	-2.172	Reject
WL-2A, WL-2B	WL & WL	2.4	454	0.108	0.592	3.891	Reject

Note: WL = Wireline 1.125" Cone

The statistical comparison of the pore pressure data indicates that cone geometry has an effect on the excess pore pressure measured. This is not an unexpected result, since excess pore pressure is created by cavity expansion which is a result of displacing the volume of soil occupied by the cone. Past experience has shown that these differences may be predicted based on a physical interpretation. Further study is planned to explore this issue.

In two field tests, the variability in differences between measurements taken with the same ASTM standard cone geometry was compared to the variability between measurements taken with a standard cone and the wireline tool. Statistical analyses were performed which rejected, with 95% confidence, the hypothesis that the results differed with respect to central tendency. In other words, we can be 95% certain that the tip and sleeve stress measurements produced by the wireline cone do not differ from ASTM standard cone measurements.

Refusal Depth

Refusal depth of the wireline system was compared to that of conventional CPT under identical conditions during the field evaluation at M-basin, SRS. The table below shows refusal depth with and without rod expanders to the refusal depth of conventional CPT using a 1.75-inch diameter rod string.

Table 4. Comparison of refusal depths for wireline system, with and without rod expanders, versus conventional CPT.

Penetration ID	System	Rod Diameter	Depth to Refusal
WL-2	Wireline without expanders	5.1 cm (2.0 in)	16.2 m (53.1 ft)
WL-2A	Wireline without expanders	5.1 cm (2.0 in)	15.8 m (51.8 ft)
WL-2B	Wireline without expanders	5.1 cm (2.0 in)	15.7 m (51.6 ft)
WL-2D	Conventional with expanders	4.4 cm (1.75 in) (2.00-in expanders)	44.5 m (146 ft)
WL-2E	Wireline with Expanders	5.1 cm (2.0 in) (2.25-in expanders)	> 33.2 m (109 ft)

With expanders, performance of the wireline system far exceeded expectations, and refusal was not encountered before running out of rods. Therefore, the 33.2-meter (109-foot) depth reported does not reflect refusal. Based on these data, we anticipate little compromise, if any, in the maximum penetration depth achievable with the 2-inch diameter wireline system versus the 1.75-inch diameter conventional CPT system.

APPLICATION

Cost Savings

In practice, CPT services are sometimes contracted at daily rates, and sometimes per foot penetrated. The cost savings herein are predicted based on a per day contract structure, and the time savings afforded by the wireline system for a particular task (i.e., for conducting piezocone characterization only, where sealing the hole created is also required).

Data obtained in the field evaluation indicate the wireline system offers a 24% saving in time and thus cost. For this particular activity, these data compare the process of (a) conducting a single penetration to a depth of 51.8 meters using the wireline piezocone tool, exchanging tools with the rod string embedded, and grouting out with the wireline grouting module, to the process of (b) penetrating to the same depth using a conventional 1.75-in CPT piezocone, withdrawing the rod string, re-penetrating the same location using a conventional grout tip, and grouting out. The table below summarizes these findings.

Table 5. Summary of Time/Cost Comparison

Description	Time to Complete Task
Conventional CPT Process	1 hour, 32 minutes
Wireline CPT Process	1 hour, 10 minutes
Time Savings	22 minutes
Time/Cost Reduction	24%

It is important to note that in the conventional process, to avoid the time required to unthread the piezocone umbilical from the rod string and re-thread the string with the grout tube, a second full set of rods must be maintained on the CPT rig pre-threaded with a grout tube.

Although a cost reduction of only 24% relative to conventional CPT was demonstrated for the process of piezocone characterization and grouting of the hole created, this application requires the least amount of re-penetration of all conventional applications. In other applications, such as multiple depth soil sampling, greater savings of time and cost are anticipated. The greatest cost savings will be realized in mixed applications, such as a combination of characterization and sampling, where, in addition to reducing re-penetration, the wireline approach will eliminate the need to move the CPT rig to a new location each time a new process of initiated.

Piezocone Validation

The performance of the wireline piezocone was validated against that of ASTM standard geometries. Therefore, the wireline piezocone can be used with confidence during site characterization activities and the data can be compared directly to existing or future ASTM standard cone measurements.

FUTURE ACTIVITIES

Tool Shortening

The 18-inch core barrel length planned for development under Option 1 of the contract, will be shortened to 12 inches to enable completely reliable retrieval and re-deployment of wireline tools. Because the core barrel length defines the distance between the locking mechanism and cutting mouth for all wireline tools, shortening the core barrel will shorten all tools, thus alleviating the tendency to bind within the rods under difficult, rod-deflecting geologic conditions. Joe Rossabi (WSRC) of the DoE Site Characterization and Penetration System (SCAPS) program witnessed the field evaluation, expressed intense interest in the development of a wireline soil sampler, and noted that a 12-inch soil core is sufficient for virtually all sampling applications typical at SRS.

Additional Tool Development

In addition to the wireline soil sampler planned for development under Option 1, strong interest was expressed by the potential end-user community in the potential for the wireline system to enable reliable collection of multiple depth water samples. Currently, reliable application of the multiple-depth water samplers requires them to be continuously purged with inert gas or de-ionized water to keep the screen from clogging with fine-grained particles during a penetration. The possibility of developing a tool which shields the inlet screen during penetration to avert clogging has been discussed. The wireline system configuration affords the ideal opportunity for shielding the inlet screen of a multiple depth water sampler during probe advancement by partial withdrawal within the rod string. Additionally, other sensors could be used for characterization, and a water sample collected wherever desired by simply replacing the real-time characterization tool with the water sampler tool. These advantages strongly support the development of a wireline water sampling tool.

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